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On the occurrence of dwarf nova outbursts in post novae

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Abstract We show that irradiation of the accretion disc by the white dwarf limits the occurrence of dwarf nova outbursts in post nova accretion discs. After the nova explosion, the white dwarf has to cool for up to ~ 100 yr – depending on the orbital period (i.e., disc size) and the temperature of the white dwarf after the nova-eruption – before the disc can begin producing dwarf nova outbursts. During this time the inner disc is maintained in a hot, ionised state. Using these calculations, we interpret the long-term photometric variability of the post nova V446 Her (Nova Her 1960) which shows today regular dwarf nova outbursts. As the white dwarf in V446 Her continues to cool over the next $\sim$10-20 yr, we predict an increase in the amplitude of outbursts and a decrease of the outburst frequency, because the decreasing irradiation of the accretion disc should allow an increasing annular extent of the accretion disc to participate in limit cycle oscillations.

Key words: accretion, accretion discs - binaries: close - stars: individual: V446 Her - novae, cataclysmic variables.

1. Introduction

Although nova eruptions and dwarf nova outbursts may resemble each other in some cases[1], the physical mechanisms behind the outbursts are entirely different: a nova eruption arises when hydrogen-rich material accreted onto the surface of a white dwarf ignites under degenerate conditions (see Starrfield et al. 1998 for a review); dwarf novae outbursts are thought to result from thermal instabilities associated with hydrogen ionisation in an accretion disc (see Cannizzo 1993 for a review and Ludwig et al. 1994 for a detailed parameter study).

It is clear that the class of cataclysmic variables (CVs), close binaries containing a white dwarf accreting from a less massive main-sequence companion, provides numerous potential novae progenitors (pre-novae). In fact, almost all CVs *should* suffer nova eruptions repeatedly during their lives. To our knowledge, no system became a nova *after* it had been classified as a CV. However, a large number of nova remnants (post novae) have been found to be CVs after they attracted attention by erupting (novae may arise, of course, on a white dwarf accreting hydrogen-rich material in other environments, e.g. in a symbiotic binary). Among the wide variety of known CV subtypes, most post novae were found to have rather high mass transfer rates $\dot{M}$, and, thus, fall into the class of novalike variables[2] Only in a small number of cases were quasiperiodic brightenings observed in post novae, identifying those systems to be dwarf novae (Livio 1989).

In this paper, we analyse the circumstances under which a post nova will evolve into a dwarf nova following the nova eruption. In the next two sections we calculate the irradiation of the accretion disc by the hot white dwarf, and estimate the amount of time required for a post nova to cool to the point that it may begin exhibiting dwarf nova outbursts. We then discuss our results in the context of the post nova with the best observational coverage to test our predictions – V446 Her.

2. White dwarf cooling in classical novae

Even though a large part of the accreted hydrogen-rich material is ejected during the nova eruption, a significant amount of hydrogen is left over in the remaining envelope, which rapidly returns to hydrostatic equilibrium (MacDonald 1996). The nova remnant experiences steady-state hydrogen shell burning until the nuclear fuel is exhausted, and is consequently heated to effective temperatures of several 10^5 K. The turn-off times of the burning envelope which have been observed with ROSAT for a small number of novae are of the order of years, e.g. 1.8 yr in V1974 Cyg

[1] In fact, a number of large amplitude/low outburst frequency dwarf novae are found in the lists of nova remnants, the most famous example being the short-period dwarf nova WZ Sge (Duerbeck 1987).

[2] Note that the published mass transfer rates were determined generally under the assumption that the disc luminosity arises from viscous dissipation only. However, irradiation by the hot white dwarf contributes significantly to the observed disc luminosity in young post novae.

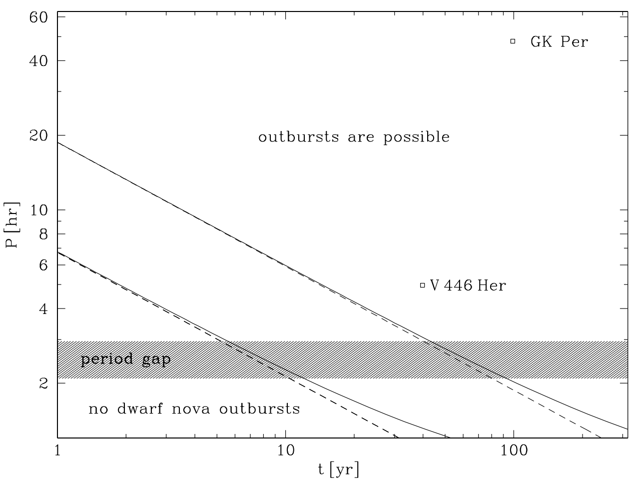

Figure 1. Irradiation limits on the occurrence of dwarf nova outbursts as a function of time after nova outburst and orbital period. We use initial effective temperatures $T_{\rm wd} = 5 \times 10^5$ K (upper curves) and $T_{\rm wd} = 3 \times 10^5$ K (lower curves). The solid lines represent calculations including a boundary layer luminosity corresponding to $\dot{M}_{\rm wd} = 10^{17}\,{\rm g\,s^{-1}}$, whereas the dashed lines are calculated using only the luminosity of the cooling white dwarf. Note that $t = 0$ corresponds to the end of the hydrogen shell burning phase, which might last for up to ~ 10 yr after the actual nova eruption.

(Krautter et al. 1996) and 10 yr in GQ Mus (Shanley et al. 1995). Additional support for turn-off times on the order of years comes from monitoring of the ultraviolet luminosity of a number of post novae following their eruption (González-Riestra et al. 1998).

Prialnik (1986) modelled the evolution of a classical nova through a complete cycle of accretion, outburst, mass loss, decline and resumed accretion. During the decline, the cooling of the white dwarf can be fit with a power-law of the form

$$L \propto t^{-1.14}, \tag{1}$$

where L denotes the luminosity of the white dwarf and t the time after the nova explosion. Prialnik's theoretical model is confirmed by Somers & Naylor (1999), who derive the cooling rate of the white dwarf using B band observations of the irradiated secondary in V1500 Cygni and find

$$L \propto t^{-0.94\,\pm\,0.09}. \tag{2}$$

3. Irradiation of the disc by the white dwarf

External irradiation of the disc by the hot central source can suppress the thermal instabilities particularly in the inner disc regions. In the context of soft X-ray transients, Tuchman et al. (1990) and Mineshige et al. (1990) calculate the thermal equilibrium structure of externally irradiated accretion disc annuli assuming that the irradiation flux is thermalized in the photosphere of the disc. King (1997) explains the UV-delay in dwarf novae taking into account irradiation from the white dwarf which truncates the inner disc. Hameury et al. (1999) confirm this claim only for hot white dwarfs ($T_{\rm wd} \geq 40\,000$ K) and find that the depletion of the inner disc must create several small outbursts between the main outbursts, contrary to observations. Leach et al. (1999) explain the low states of VY Scl stars as being due to the interplay of irradiation from hot white dwarfs and low mass transfer rates.

For completeness we note that the motivation of King (1997) and Hameury et al. (1999) was to account for the "problem of the UV delay" in dwarf novae, although the effects of irradiation of the inner disc are of general interest for the operation of the accretion disc limit cycle mechanism. Smak (1998) critically re-examined the basis for the claim of a problem, and finds that there does not seem to be one. Previous studies which had claimed there to be a problem had utilised various simplifications in their time dependent models which turned out to be critical - such as the neglect of a variable outer boundary. The contraction of the accretion disc during quiescence has the effect of increasing the local surface density in the outer disc, and thereby promoting disc instabilities which begin at large radii. These so-called "outside-in" (Cannizzo et al. 1986) or "type A" (Smak 1984) outbursts in which a narrow spike of enhanced surface density propagates from the initial site of the instability to the inner edge, are able to produce outbursts with the observed delay.

In this work we calculate the structure of irradiated accretion discs in non-magnetic post novae, taking into account the time dependent flux of the white dwarf cooling down from the hydrogen shell burning phase, as well as the luminosity of the boundary layer resulting from accretion onto the white dwarf. The luminosity of the white dwarf is given by

$$L_{\rm wd}(t) = 4\pi\, {R_{\rm wd}}^2\, \sigma\, T_{\rm wd}^4(t) \,\propto\, t^{-1.14}, \tag{3}$$

where $R_{\rm wd}$ and $T_{\rm wd}$ denote the radius and the effective temperature of the white dwarf, respectively, and σ is the Stefan-Boltzman constant. The boundary layer luminosity is

$$L_{\rm BL} = \alpha_{\rm BL}\, \frac{G\, M_{\rm wd}\, \dot{M}}{R_{\rm wd}} \tag{4}$$

where G is the gravitational constant and, as in Stehle & King (1999) and Leach et al. (1999) we take $\alpha_{\rm BL} = 0.5$. Assuming that the boundary layer luminosity is radiated by the entire surface of the white dwarf and the disc is geometrically thin, the time-dependent flux $F_{\rm irr}(t)$ irradiating the disc at the radius R is given by

$$F_{\rm irr}(t) = (1-\beta)\frac{L_{\rm BL} + L_{\rm wd}(t)}{2\,\pi\,\sigma\,{R_{\rm wd}}^2}\,\frac{1}{\pi}[\arcsin\rho - \rho(1-\rho^2)^{\frac{1}{2}}], \tag{5}$$

(Adams et al. 1988; King 1997), where β is the albedo, $\rho = R_{\rm wd}/R$ and $t = 0$ at the end of the hydrogen shell burning phase. Throughout this paper we follow King (1997) in adopting $\beta = 0.5$.

If the irradiation temperature ($\sigma T_{\rm irr}^4 \equiv F_{\rm irr}$) exceeds $T_{\rm H} \sim 6500\,{\rm K}$ the hydrogen in the disc is fully ionised independent of the accretion rate (van Paradijs 1996) Thus, setting $T_{\rm irr} \geq T_{\rm H}$ at the outer edge of the disc ($R = R_{\rm out}$) gives a limit of the irradiation flux which suppresses the disc instability. Using standard equations (Eggleton 1983; Frank et al. 1992) and assuming that the outer disc radius $R_{\rm out}$ is 70 % of the primary's Roche lobe radius, we obtain the outer radius of the accretion disc as function of the orbital Period P and the binary mass ratio $q = M_2/M_{\rm wd}$. We used $q = 0.5$ for all calculations throughout the paper as we are mainly interested in systems above the period gap.

We can now estimate how long disc instabilities in the accretion discs of post novae are suppressed due to irradiation, where we assume either $\dot{M} = 0$ or $\dot{M} = 10^{17}{\rm g\,s^{-1}}$, as typical for dwarf novae above the period gap (for much higher accretion rates, the disc remains in a stable, hot state anyway). Fig. 1 shows the results for initial temperatures of $T_{\rm wd}(0) = 5 \times 10^5{\rm K}$ and $T_{\rm wd}(0) = 3 \times 10^5\,{\rm K}$. Apparently, disc instabilities, and, hence, dwarf nova outbursts, should typically be suppressed for ∼5–50 yr, and up to ∼100 yr if the white dwarf is strongly heated during the nova eruption. It is also clear that the size of the disc is a crucial parameter: the irradiation from the white dwarf can suppress the instability over the entire disc only for orbital periods $P_{\rm orb} \lesssim 20\,{\rm hr}$. The contribution of the boundary layer luminosity becomes important only after ∼ 5 yr at the earliest.

It is important to note that our results are lower limits on the time scale on which irradiation from the white dwarf suppresses dwarf nova outbursts in post novae for the given disc albedo: (a) in order to produce significant dwarf nova outbursts, the disc instability has to affect on considerable parts of the outer disc and not only the outer edge (we focus on this subject in the next section) and (b) the disc may be flared and therefore intercept more flux from the white dwarf than described by Eq.(5), which assumes a flat disc.

4. Dwarf novae among post novae?

Accretion disc instabilities and their observational consequence, dwarf nova outbursts, can occur in a non-magnetic cataclysmic variable, if under the assumption of stationary accretion, the disc at its outer rim is colder than the ionisation temperature of hydrogen, $T_{\rm H}$. As described above, two factors determine the disc temperature at a given radius: the mass transfer rate and the irradiation field from the white dwarf.

While most post novae seem to have no outbursts, a small number of post novae show repetitive optical brightenings that are reminiscent of dwarf nova outbursts (Livio 1989; Honeycutt et al. 1998a). The post novae for which this outburst behaviour is best documented are GK Per (= Nova Per 1901), which shows outbursts of ∼ 3 mag every ∼ 1000 d, and V446 Her (= Nova Her 1960), which shows outbursts with an amplitude of ∼ 2.5 mag and a recurrence time of ∼ 23 d (Honeycutt et al. 1998b).

The presence of outbursts in GK Per is not surprising: The critical mass transfer rate below which outbursts are possible is $\dot{M}_{\rm cr} \simeq 10^{16}$ g s^{-1} $R_{10}^{2.6} m_1^{-0.87}$, where R_{10} is the outer disc radius in units of 10^{10} cm and m_1 is the primary mass in solar units (Cannizzo et al. 1988). The large disc size ($P_{\rm orb} = 2\,{\rm d}$) for GK Per means that $\dot{M}_{\rm cr} \simeq 2 \times 10^{19}\ {\rm g\,s^{-1}}$, which ensures that disc instabilities are possible even at very high mass transfer rates and almost independent of the mass transfer rate. Indeed, the outbursts observed in GK Per have been successfully modelled within the disc instability scenario (Cannizzo & Kenyon 1986; Kim et al. 1992).

By contrast, V446 Her has $P_{\rm orb} = 4.97\,{\rm h}$ (Thorstensen & Taylor 2000), which places it among a number of "normal" dwarf novae longward of the $2-3$ hr period gap. The dwarf nova nature of V446 Her is confirmed by its spectrum which is typical for this class (Thorstensen & Taylor 2000). The presence of dwarf nova outbursts in V446 Her indicates that the accretion rate cannot be too high.

In the previous section we assumed that the disc instability is suppressed for $T_{\rm irr} \geq 6500\,{\rm K}$, which is a reasonable but somewhat simplified statement. In order to get more detailed results, we re-derive the accretion rate above which the disc instability is suppressed, $\dot{M}_{\rm cr}$, from calculations of the vertical structure of irradiated accretion discs. Our computations are based on the vertical structure code written by one of us (JKC) and described in Cannizzo & Wheeler (1984) and Cannizzo & Cameron (1988) which we have modified to include the effects of external irradiation. Assuming that the external flux is thermalized in the surface layer, we set

$$\sigma T_{\rm s}^4 = F_{\rm visc} + \sigma T_{\rm irr}^4 \tag{6}$$

at the outer boundary, where $T_{\rm s}$ is the photospheric temperature, $F_{\rm visc}$ the energy flux arising from viscous dissipation and $T_{\rm irr}$ the irradiation temperature defined above (Hameury et al. 1999). We calculate the modified vertical structure for $M_{\rm wd} = [0.5, ..., 1.3]\,M_{\odot}, \alpha = [0.005, ..., 1]$, $R = [0.1, ..., 10] \times 10^{10}\,{\rm cm}$ and $T_{\rm irr} = [0, ..., 12] \times 10^3\,{\rm K}$. For the non-irradiated disc (i.e. $T_{\rm irr} = 0$), we obtain

$$\dot{M}_{\rm cr} = 9.5 \times 10^{15}\,{\rm g\,s^{-1}}\,R_{10}^{2.64}\,\alpha^{0.01}\,m_1^{-0.88}. \tag{7}$$

This result is in good agreement with values derived previously (Cannizzo et al. 1988; Ludwig et al. 1994; Hameury et al. 1998).

Fig. 2 shows examples of the thermal equilibrium curves for different irradiation temperatures. Irradiation has a significant influence on the ionisation state of the disc for $\log(T_{\rm irr}) \geq 3.5$. The critical accretion rate, below which the disc becomes unstable, decreases with increasing irradiation until the external flux becomes strong enough to hold the disc in the hot stable state independent of the accretion rate. We find that the irradiation temperature $T_{\rm irr,s}$ for which $\dot{M}_{\rm cr}$ vanishes is a slightly decreasing function of R_{10} and α, but nearly independent of m_1:

$$T_{\rm irr,s} = 7382\,{\rm K}\,\alpha^{-0.07}\,R_{10}^{-0.03}. \qquad (8)$$

The decrease of $\dot{M}_{\rm cr}$ between the non-irradiated case (Eq. 7) and the suppression of the instability is approximately given by:

$$\dot{M}_{\rm cr}^{\rm irr} = \dot{M}_{\rm cr}\left(1 - \frac{T_{\rm irr}^{7.2}}{T_{\rm irr,s}^{7.2}}\right), \qquad (9)$$

where $T_{\rm irr,s}$ and $\dot{M}_{\rm cr}$ given above. Using the result of our parameter study, i.e. $\dot{M}_{\rm cr}^{\rm irr}(M_{\rm wd}, R, T_{\rm irr}, \alpha)$, combined with Eq. (5) and assuming $T_{\rm wd}(0) = 3 \times 10^5$ K after the nova event, we find that the limit cycle instability can operate now (i.e. 40 yr after the 1960 nova) only between $\sim 1.2 \times 10^{10}$ cm and $R_{\rm out} \simeq 3.8 \times 10^{10}$ cm in V446 Her (Fig. 3). This might be enough to produce significant dwarf nova outbursts but the continuing cooling of the white dwarf should lead in the future to an increase of the outburst amplitude as well as to longer quiescence periods.

Assuming that the mass transfer rate in V446 Her is indeed low enough to permit a disc instability limit cycle, we compare now our estimates of irradiation suppression of dwarf nova outbursts with the long-term photometric history of the system.

The pre-nova showed brightness fluctuations between $V \sim 18 - 15$, which bear some resemblance to dwarf nova outbursts, even though the rise time of the single well sampled "flare" seems too slow compared to a typical dwarf nova outburst (Robinson 1975). Stienon (1971) reports 9 photometric measurements of the post nova obtained between 22 September 1968, and 26 September 1970, i.e. 8–10 yr after the nova eruption, all of which show the system at $m_{\rm pg} \sim 15.8$. Finally, the systematic RoboScope photometry of Honeycutt et al. (1998a), starting in 1990, shows V446 Her at a quiescent magnitude of $V \sim 18$ with regular outbursts reaching $V \sim 15.5$. It appears very unlikely that all of Stienon's measurements caught the system at the maximum of an outburst, and we believe that dwarf nova outbursts were suppressed in V446 Her for at least ten years after the nova eruption in 1960. Unfortunately, we do not know how long the hydrogen shell burning lasted in V446 Her, and it is not clear at which point between 1970 and 1990 the dwarf nova outbursts resumed. Therefore, we can not give a quantitative estimate of $T_{\rm wd}(0)$.

5. Discussion

Taken at face value, the decrease of the optical brightness observed in V446 Her over several decades following the nova eruption and the onset of dwarf nova outbursts $\sim 1 - 3$ decades after the nova eruption could be interpreted simply as a decline of the accretion rate, being higher than the critical accretion rate for at least the first decade after the eruption, and being below the critical rate in the 1990's.

Such a decline of the accretion rate in post novae is the hallmark of the "hibernation scenario", which was invoked by Shara et al. (1986, see Shara 1989 for a review) to solve discrepancies between nova theory and observations and to account for the low observed space density of CVs when compared to the number of nova eruptions in our Galaxy or M31. In the hibernation scenario, irradiation of the secondary star by the hot white dwarf should keep the mass transfer rate high after the nova eruption for a limited period of time, after which the mass transfer rate decreases to very low values. The post novae should, hence, appear at first as a novalike variables (for many decades to a century) with stable hot accretion discs, and evolve thereafter into inconspicuous low $\dot{M}$ CVs. Thus, in the hibernation scenario it appears plausible that most "fresh" post novae have indeed high accretion rates, and that the oldest recovered novae are intrinsically very faint (e.g Shara et al. 1985).

On observational grounds, the hibernation scenario has been challenged, e.g. Naylor et al. (1992) and Weight et al. (1994), but obtained also some support: Vogt (1990) and Duerbeck (1992) found a gradual decrease in the visual brightness during the final decline of novae and interpret this result as an evidence for a decrease of the mass transfer rate in these systems, consistent with the hibernation scenario. However, the latter point needs to be considered with some care: as already mentioned in the introduction, irradiation by the hot white dwarf significantly contributes to the observed disc brightness. As the white dwarf cools from the nova outburst, the decreasing amount of irradiation will result in a decrease of the observed disc brightness, and, hence, mimick a decrease of the accretion rate.

A valuable alternative to the hibernation model that can explain at least the fact that only in a small number of cases dwarf nova outbursts were observed in post novae (and pre novae) is the mass transfer cycle proposed by King et al. (1995) in which the accretion-induced irradiation of the secondary drives a limit cycle with a period of $\sim 10^6 - 10^7$ yr. In this cycle, a CV spends similar times in states of high and low accretion rates, appearing as a novalike variable or as a dwarf nova. It is then clear that the probability that a CV turns into a nova is highest during the phase of high mass transfer, which naturally explains why most post novae are novalike variables. Of course, in some low $\dot{M}$ CVs the accreted envelope will also reach the critical mass for a nova eruption, and V446 Her might be such a case.

In this scenario, pre novae and post novae would have the same characteristics, which is in agreement with the analysis of Robinson (1975), who found that in most novae the pre-eruption and post eruption magnitudes are very similar.

6. Conclusion

We have calculated the effect that irradiation by the heated white dwarf in a post nova has on the structure of an accretion disc. We find that, even if the accretion rate in such a system is low enough to permit disc instabilities, irradiation from the white dwarf suppresses dwarf nova outbursts for up to $\sim$ 100 yr. In the case of V446 Her our calculations predict an increase of the outburst amplitude and a decrease of the outburst frequency as the white dwarf keeps on cooling down. We encourage long-term monitoring of V446 Her in order to detect any evolution of the outburst pattern.

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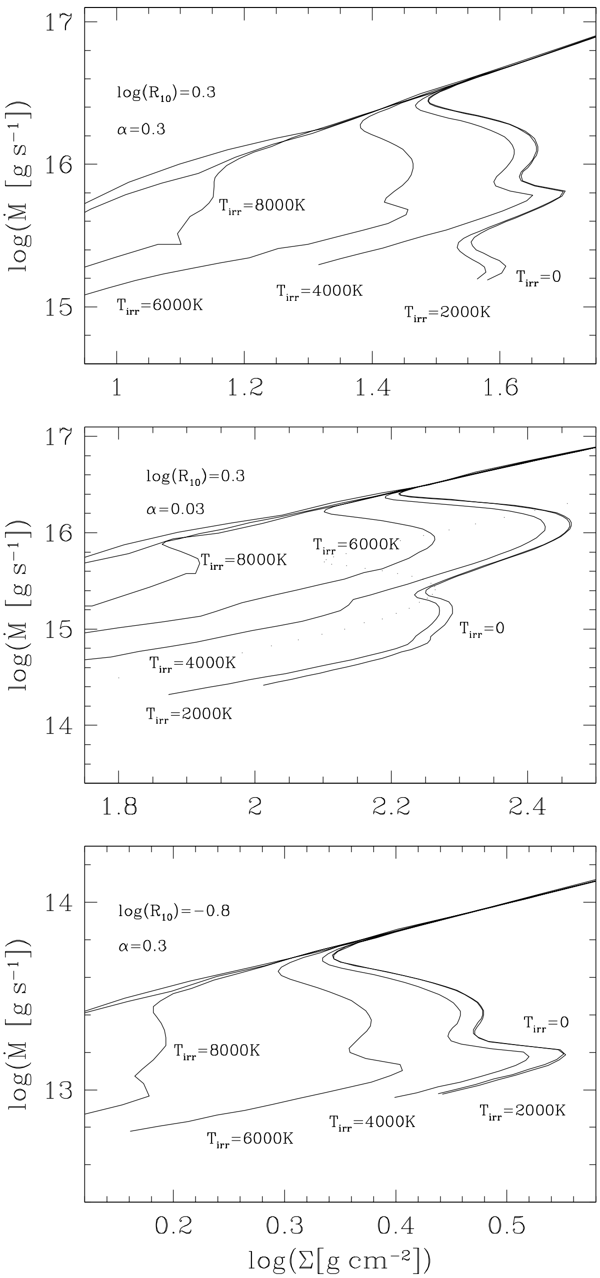

Figure 2. The vertical equilibrium curves for irradiation temperatures of $T_{\rm irr} = [0, 2, 4, 6, 8, 10, 12] \times 10^3$ K (right to left) and a white dwarf mass of $M_{\rm wd} = 1.3\,M_{\odot}$. Assuming a relatively high α and at a large radius, the disc instability is suppressed for an irradiation temperature $T_{\rm irr} = 8000$ K (top panel), while it is not fully supressed for a lower α (middle panel) or at a smaller radius (bottom panel) and the same irradiation temperature $T_{\rm irr} = 8000$ K. The external irradiation temperature necessary to suppress the instability increases with decreasing radius and decreasing α (see Eq. (8)). Note the different scalings.

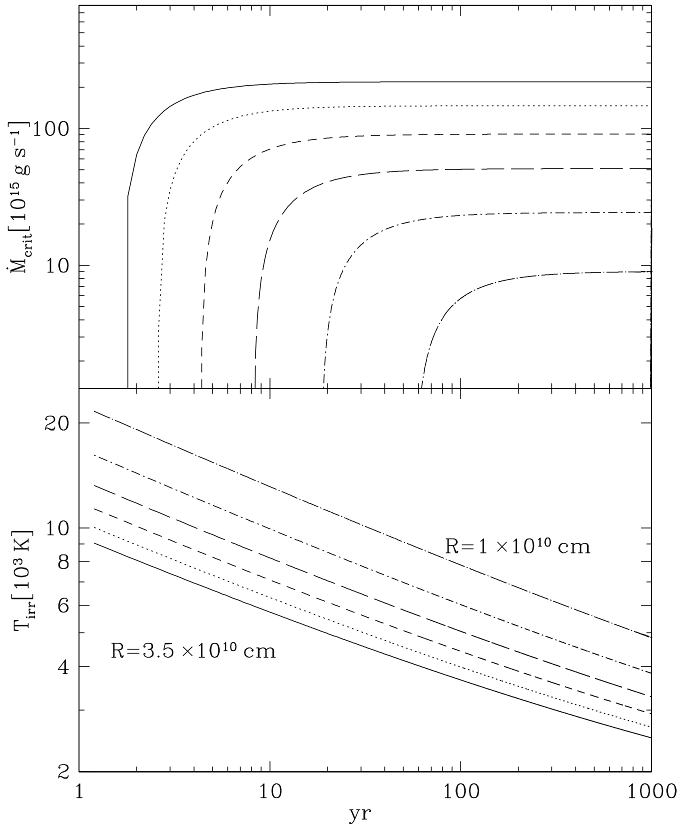

Figure 3. The critical accretion rate and the irradiation temperature as a function of time for different disc annuli ($R = [3.5, 3, 2.5, 2, 1.5, 1] \times 10^{10}$ cm), $\alpha = 0.3$ and $m_1 = 0.6$.